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# Modeling of Mechanism of Plan Formation by New Caledonian Crows

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## Abstract

The current paper analyzes the mechanism of planning by New Caledonian crows. The mechanism uses predictions of results of actions. Namely, our model suggests that for a given situation and a particular action, the crow predicts the next situation. The mechanism of planning includes: 1) generation of needed predictions, 2) formation of a simple knowledge database that describes situations, actions, and results of actions, 3) formation of the plan of actions that result in a goal situation. The knowledge database is a table; each row of the table represents some initial situation, an action, the predicted next situation, and the estimation of a distance between the considered situations and the goal situation. The mental process of plan formation uses this knowledge database. The plan is the chain of consecutive actions. Beginning from the starting situation and executing this chain of actions, the crow obtains the goal situation.

**Keywords:** modeling of animal behavior, mechanism of plan formation, chain of consecutive actions

## 1 Introduction

The current paper describes a model of a process of plan formation by New Caledonian (NC) crows. Our model is based on the biological experiment on NC crows [1]. In that work, NC crows were preliminary trained to execute particular elements of a rather complex behavior. After the preliminary training, the crows should solve the three-stage problem. The solution includes the following particular elements: (1) to pull up a short stick tied to the end of a string and to release this stick, (2) to extract a long stick from a barred toolbox by means of the short stick, and (3) to extract the food from a deep hole by means of the long stick. It was impossible (a) to extract the food from the

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deep hole by means of the short stick and (b) to extract the long stick from the barred toolbox by means of a bill. Therefore, in order to reach the food, the crow had to execute the ordered chain of sequential actions  $1 \rightarrow 2 \rightarrow 3$ . Designing our model of the mechanism of plan formation, we take into account the method implemented in our previous model of planning behavior by fish [2].

The current model differs from the simple scheme of plan formation [3]; here we pay a special attention to the mechanism of plan formation by NC crows. Next section outlines the biological experiment on NC crows [1]. Then we describe the model of the mechanism of plan formation by NC crows. The model is analyzed by means of computer simulation.

## 2 Biological Experiment on NC Crows

Let us consider needed details of the biological experiment on NC crows [1]. Two groups of crows were investigated: the component group and the innovation group. In the course of the preliminary training, the component group obtained almost full knowledge about three particular elements of the mentioned three-stage problem. The innovation group obtained some knowledge about first and third elements, but not about the second element (extracting the long stick from the barred toolbox by means of the short stick). The component group included three crows; the innovation group included four crows.

After the preliminary training, the complex three-stage task was presented to the crows of both groups. The starting situation for both groups of crows was the following: the short stick is tied to the end of the string; the long stick is in the barred toolbox; the food is in the hole. The crows of the component group solved the three-stage problem on the first trial. Two crows of the innovation group solved the problem on the first trial, whereas other two crows of this group solved the problem on the third and fourth trials. All crows solved the problem after visual inspecting the apparatus (the barred toolbox, the deep hole with the food, and the long and short sticks). The time needed to inspect the apparatus was relatively short for the component group and rather long for the innovation group. The crows of the innovation group executed some testing actions during this inspection. We can also assume that the crows conducted certain “mental experiments” while inspecting the apparatus and further forming a mental plan of solving the whole three-stage problem. See [1] for details.

## 3 Mechanism of Plan Formation

### 3.1 Description of the Model

We assume that each crow stores results of the preliminary training in the form of prediction of the next situation ( $S_{next}$ ) for the current situation and action ( $S_{current}, A_{current}$ ):

$$\{S_{current}, A_{current}\} \rightarrow S_{next}.$$

The main situations and actions are:

$S_1$ : the short stick is tied to the end of the string; the long stick is in the barred toolbox; the food is in the deep hole

$S_2$ : the short stick is free; the long stick is in the barred toolbox; the food is in the deep hole

$S_3$ : the long stick is free; the food is in the deep hole

$S_4$ : the food is free

$A_1$ : to pull up the string and to release the short stick tied to the end of the string

$A_2$ : to extract the long stick from the barred toolbox by means of the short stick

$A_3$ : to extract the food from the deep hole by means of the long stick

$S_1$  is the starting situation;  $S_4$  is the goal situation.

Crows store some predictions after the preliminary training and generate other needed predictions during plan formation by means of mental imagination and real experimental testing.

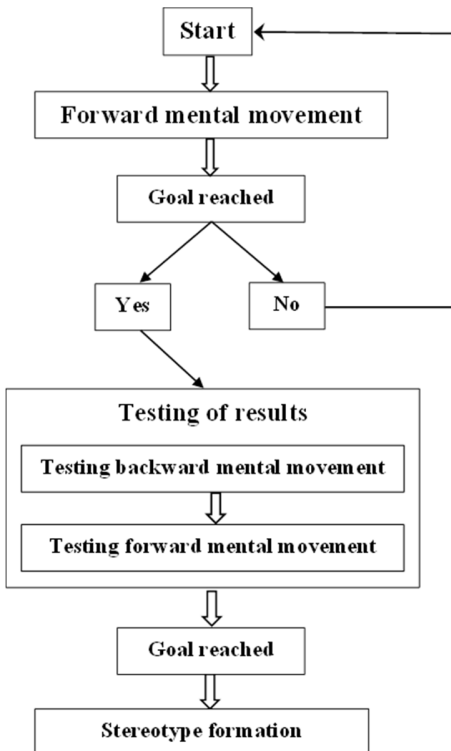
At the preliminary training, all the crows were trained to do the prediction  $\{S_3, A_3\} \rightarrow S_4$  (using the long stick, the crow can extract the food from the deep hole). The component crows can also do the prediction  $\{S_2, A_2\} \rightarrow S_3$  (it is possible to extract the long stick from the barred toolbox by means of the short stick). Any crow could not make the needed prediction  $\{S_1, A_1\} \rightarrow S_2$ ; although at the preliminary training, the crows can pull up the string and to release a piece of food tied to the end of the string [1], i.e. the crows could guess this prediction.

Note that considered predictions are similar to simple functional systems [4]. The next situation  $S_{next}$  can be considered as the acceptor of the result of the current action at these predictions.

We believe that the crows have the assurances of the correct predictions; these assurances of results of actions are similar to assurances of predictions in the models of fish exploratory behavior in mazes [2].

We suppose that the mechanism of plan formation includes the following steps (Figure 1):

- 1) The forward mental movement (until the correct path to the goal is mentally reached)
- 2) The testing of this path by means of testing backward and forward mental movements
- 3) The generation of the stereotype of the goal-directed behavior after the checking of the path to the goal at the testing.



**Figure 1:** The scheme of plan formation. The forward mental movement is the movement from the starting situation  $S_1$  to the goal situation  $S_4$ . The backward mental movement is the movement in the reversed direction: from  $S_4$  to  $S_1$ . At testing backward mental movement, the crow evaluates the distance between considered and goal situations and forms the knowledge database. At testing forward mental movement, the crow uses the knowledge database and selects actions that reduce the distance from the goal situation. After successful verification at the testing of results, the crow forms the stereotype of the goal-directed behavior

At the forward mental movement, the crow analyzes ways to reach the goal situation  $S_4$  from the starting situation  $S_1$ . The crow represents the forward movement (from  $S_1$  to  $S_4$ ) mainly mentally; however, sometimes the crow tries to execute some actions really. At this forward movement, the crow guesses possible results of its action. The component crow guesses the correct useful prediction

$\{S_1, A_1\} \rightarrow S_2$  with probability  $P_1$ . The innovation crow guesses the correct useful predictions  $\{S_1, A_1\} \rightarrow S_2$  and  $\{S_2, A_2\} \rightarrow S_3$  with probabilities  $P_2$  and  $P_3$ , respectively ( $P_1 > P_2 > P_3$ ). The crow mentally represents the forward movement several times, until it finds the scheme of reaching of the goal situation  $S_4$ . This process of the reiterative forward movement is shown by the upper loop in Figure 1.

During this mental movement, the crow obtains assurances  $A_s$  of predictions of results of particular actions.  $A_s(S_{current}, A_{current}, S_{next})$  is the assurance that the result of the current action  $A_{current}$  in the current situation  $S_{current}$  is the next situation  $S_{next}$  ( $0 \leq A_s \leq 1$ ). The maximal assurance value is  $A_{s\_max} = 1$ . It should be noted that some initial assurances  $A_s$  are obtained at the preliminary training. At the preliminary training, the component crows obtain rather high assurance  $A_{s0}$  for the predictions  $\{S_3, A_3\} \rightarrow S_4$  and  $\{S_2, A_2\} \rightarrow S_3$ . The innovation crows have initially  $A_{s0}$  only for the prediction  $\{S_3, A_3\} \rightarrow S_4$ . All other assurances are equal to 0 before the first forward mental movement. The assurances of the correct/incorrect predictions of results of actions increase/decrease at the forward mental movement. In particular, at correct predictions  $\{S_{current}, A_{current}\} \rightarrow S_{next}$ , the corresponding assurance  $A_s(S_{current}, A_{current}, S_{next})$  increases:

$$\Delta A_s(S_{current}, A_{current}, S_{next}) = d [1 - A_s(S_{current}, A_{current}, S_{next})],$$

where  $0 < d < 1$ .

One attempt at this forward mental movement corresponds to one trial of a crow in the biological experiment [1]. In some initial attempts, the modeled crows do not find the way to reach the goal situation. This is in accordance with the experimental results: in some initial trials, the innovation crows did not reach the goal.

In our model, after reaching mentally the goal situation, the crow mentally checks the way to reach the goal by means of testing backward and forward movements (see the block "Testing of results" in Figure 1).

The testing backward mental movement begins from the goal situation  $S_4$ . At the backward mental movement, the crow estimates also the distance  $\rho$  between the considered situations and the goal situation  $S_4$ ; this distance is the number of actions needed to reach the goal situation  $S_4$  from the considered situation. At the testing backward mental movement, the crow forms the knowledge database (Table 1). After reaching mentally the starting situation, the backward mental movement stops and the testing forward mental movement begins.

At the testing forward mental movement, the crow begins from the starting situation  $S_1$  and chooses the actions that reduce the distance  $\rho$ .

The result of the testing is the knowledge database represented in Table 1. Three first columns of this table is the plan of the behavior aimed to reach the goal situation  $S_4$ . The knowledge database is actually the stereotype of the goal-directed behavior. The stereotype behavior does not need the considered mental processes, therefore such behavior should occur quickly.

**Table 1:** Knowledge database

Current situation, $S_{current}$	Current action, $A_{current}$	Next situation, $S_{next}$	$\rho(S_{current}, S_4)$	$\rho(S_{next}, S_4)$
$S_1$	$A_1$	$S_2$	3	2
$S_2$	$A_2$	$S_3$	2	1
$S_3$	$A_3$	$S_4$	1	0

$\rho(S_{current}, S_4)/\rho(S_{next}, S_4)$  in this table is the distance between the situation  $S_{current}/S_{next}$  and the goal situation  $S_4$ .

### 3.2 Results of Computer Simulation

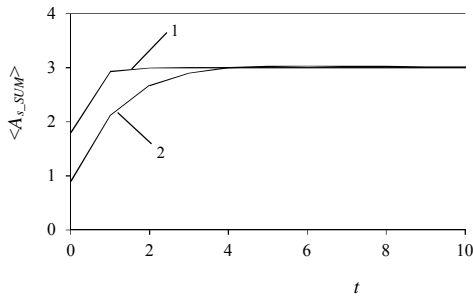
The described scheme of the mechanism of plan formation was implemented into the computer program. The parameters of computer simulation were the following:

- the initial value of a particular assurance of a prediction of a result (obtained after the preliminary training)  $A_{s0} = 0.9$ ;
- the parameter of increasing of assurances at the forward mental movement  $d = 0.5$ .
- the probabilities of guessing of correct useful actions and corresponding predictions were  $P_1 = 0.9$ ,  $P_2 = 0.7$ ,  $P_3 = 0.5$ .

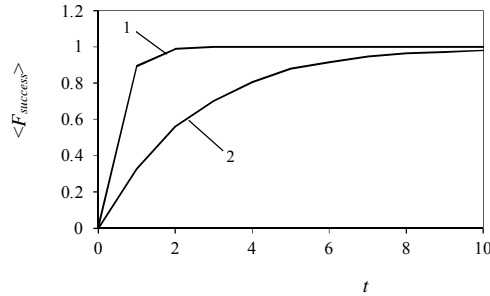
We considered the dynamics of the sum of assurances  $A_{s\_SUM}$  for all possible chains  $\{S_{current}, A_{current}\} \rightarrow S_{next}$  and the relative frequency  $F_{success}$  to find the solution of the whole three-stage problem for both component and innovation crows. To obtain the reliable characteristics of considered processes, the results of simulations were averaged for 1000 different calculations. The dependences of average sum of assurances  $\langle A_{s\_SUM} \rangle$  on time  $t$  for component and innovation crows are shown in Figure 2. One time moment in simulation corresponds to one trial in the biological experiment [1].

The dependences of average relative frequency  $\langle F_{success} \rangle$  of successful mental reaching of the goal situation  $S_4$  on time  $t$  for component and innovation crows are shown in Figure 3;  $F_{success} = 1$  means that the crow finds the goal without mistakes.

Figures 2, 3 demonstrate that the component crows find the way to reach the goal quickly, mainly at the first trial; the innovation crows find the solution to reach the goal at several first trials. These results are in accordance with the biological experiment [1].



**Figure 2:** The dependences of average sum of assurances  $\langle A_{s\_SUM} \rangle$  on time  $t$  for component (1) and innovation (2) crows



**Figure 3:** The dependences of average frequency of successful reaching of the goal  $\langle F_{success} \rangle$  on time  $t$  for component (1) and innovation (2) crows

## 4 Discussion and Conclusion

Thus, the model of the mechanism of plan formation by New Caledonian crows have been designed and analyzed. The considered mechanism is based on particular biological experiment [1]; however, the mechanism is rather general, so some parts of this mechanism could be applicable for different processes of planning the goal-directed behavior.

It should be noted that when the crow tries to execute some testing action (mentally or really) at the forward mental movement, this is similar to testing actions by agents. Such actions at interaction with environment can begin before observations [5].

We can also note that the process of the testing backward movement is analogous to the reverse replay of behavioral sequences in hippocampal place cells [6, 7].

The main features of the modeled mechanism of plan formation are the following.

1. The process of searching for the plan of goal-directed behavior includes forward and backward mental movements (Figure 1).
2. At the initial forward mental movement, the crow obtains and stores the assurances of predictions of results of its actions. The crow can iteratively repeat this forward mental movement, until it finds the way to reach the goal situation. Note that the considered assurances are similar to the assurances of predictions of results of actions in the model of searching behavior of fish in mazes [2].
3. After finding the way to the goal situation at the first time, the crow checks this way by means of testing forward and backward mental movements.
4. After checking the way to reach the goal situation, the crow forms the knowledge database that characterizes the plan of the goal-directed behavior (Table 1). The crow forms also the stereotype of this behavior.

The process of the plan formation was analyzed by means of computer simulation. The results of simulation are in qualitative agreement with the biological experiments.

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